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Cities and transport networks in shipping and logistics research

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Contents

Abstract

While shipping and logistics studies often describe the flows and networks on the level of firms and terminals rather than cities, urban studies pay limited attention to transport infrastructure and material flows. The renewal of network analysis based on complex systems will be discussed in this paper as a potential bridge between those two approaches. It particularly focuses on how transport and urban elements can be mutually integrated. The main conclusion points at the efforts to better untangle network/carrier and urban/territorial effects in the design and operation of shipping and logistics systems.

Key Words: Complex Systems; Graph Theory; Economics; Systems of Cities; Transport Geography

I. Introduction

The spatial distribution of shipping and logistics systems, which encompasses all transport modes and operations, is an increasingly important area in transport and urban studies. However, the analysis of

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transport networks includes only implicitly the urban dimension, and urban studies remain marginal in the material linkages within and among cities. In particular, transport geography has been developed in a rather autonomous manner, shifting away from mainstream geography due to its stronger specialization about transport infrastructure, actors, and operations[1]. On the other hand, urban and regional researches have increasingly focused on social and cultural aspects[2]. Such dichotomy persists nowadays in various fields, such as the New Economic Geography (NEG) where transport is approached by its cost related to the spatial agglomeration or dispersion effects[3], and transport network analysis with little reference to cities per se[4]. Even though there are contrasted evidences about the interdependencies between urban and transport development, especially in the case of ports[5] and airports[6], the shipping and logistical dimension in a system of cities and its dynamics remains an unexplored area[7].

Two main questions motivate this research: why are urban and shipping/logistics studies mutually dependent nowadays? and how did network analysis become a useful tool to further bridge urban and shipping/logistics studies? To answer them, our first argument is related to the type and amount of available geospatial information. Before the development of the Geospatial Information System (GIS), geospatial data was difficult to collect, analyze, and include in theoretical models[8]. In the last 20 years, new research pathways have emerged in the area of natural sciences favored by improved technological standards and information availability[9]. Secondly, we suggest that the complexity science provides the framework for integrating heterogeneous data sources and varied scientific perspectives into generic spatial models.

The paper attempts to synthesize a number of contributions that further bridged transport and urban studies. The critical review is limited to the level of inter-urban linkages, which poses theoretical and methodological

1 Keeling (2007); Ng (2013)
2 Hall and Hesse (2012)
3 Fujita and Mori (1996); Behrens et al. (2006); Lafourcade and Thisse (2011)
4 Ducruet and Lugo (2013)
5 Ducruet and Lee (2006); Jacobs et al. (2010 & 2011)
6 Dobruszkes et al. (2011); Neal (2011); Wang et al. (2011)
7 Bretagnolle and Pumain (2010); Beyers and Fowler (2012)
8 Waters (2006)
9 Ducruet and Beauguitte (2013)

problems to model the structure and to analyze the dynamics of a system of cities. We, primarily, review a number of classic transport network studies and recent works of urban and logistical aspects, discussing the method for merging a system of cities and transportation modes. This is followed by a review of how urban and logistical elements have been integrated in more dynamical studies of networks. The conclusion provides a crucial discussion about the legacy of previous researches and pathways for further integration between urban studies and shipping / logistics research.

II. Network structures

1. Spatial characteristics

The physical grounding of shipping and logistics systems is one key component of the category of spatial networks, where distance (e.g. Euclidian) has a strong influence on the structure and evolution of nodes and links, as opposed to other types of networks such as social, biological, and scientific collaboration networks[10]. In addition, the literature on supply chain management, global logistics, and multinational firms focuses more on invisible links as in a social network[11].

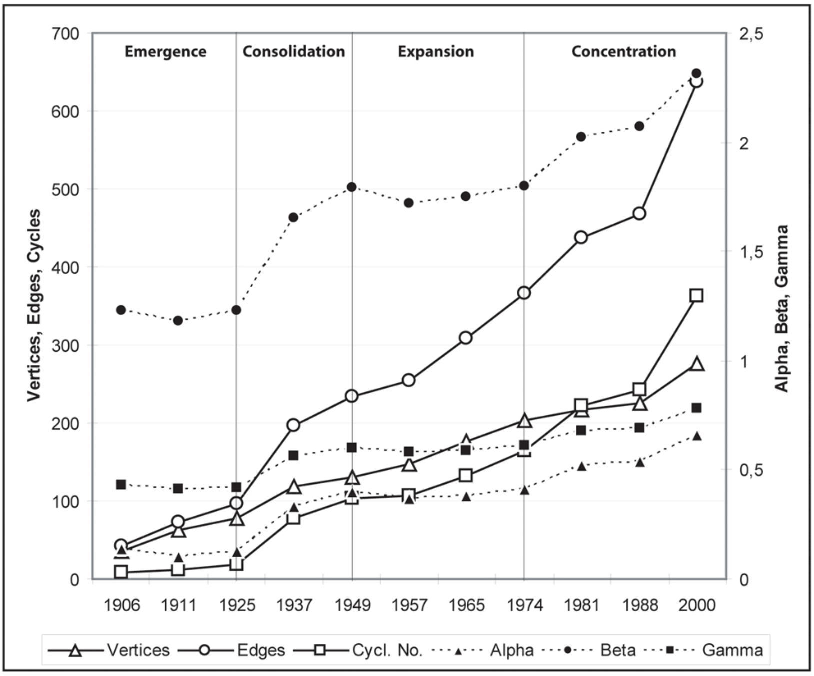
Transport networks are described by their overall morphology[12], which varies depending on each different modes[13]. They represent physical objects where nodes are associated with origin-destination and junction points, and edges are related to physical constructs in a graph having more or less overlap with the actual network[14]. One of the main sources of this information is vector data. Points, lines, and polygons are stored as a layer in the GIS or specific network visualization software nowadays[15].

Classical measures were applied to many networks such as the density and connectivity of road[16], railway[17], subway[18], and river

10 Boccaletti et al. (2006); Gastner and Newman (2004); Blumenfeld-Lieberthal (2009)
11 Rozenblat and Pumain (2006); Dornier and Fender (2007); Rozenblat (2010)
12 Kansky (1963); Garrison and Marble (1974); Béguin and Thomas (1997); Scott et al. (2005); Kurant and Thiran (2006a); Xie and Levinson (2009)
13 Banavar et al. (1999); Kurant and Thiran (2006b); Xu et al. (2007); Rodrigue et al. (2009)
14 Gleyze (2007); Rozenblat and Melançon (2013)
15 Lambert et al. (2013)
16 Garrison (1960)
17 Dancoisne (1984)

networks[19]. Figure 1 presents the application of such classic methods to the Chinese railway network[20], which allow to identify successive development stages based on the number of nodes (vertices), links (edges), and cycles (cyclomatic number) as well as the lattice degree (alpha index), density, complexity (beta index), and connectivity, completeness (gamma index). Most studies of transport networks that mention urban and regional development could only indirectly interpret urban aspects that were not part of the analysis itself[21].

<Figure 1> Topological evolution of the Chinese railway network, 1906-2000
(Source: adapted from Wang et al.[20])



It is only recently that methods of network analysis have been adapted to include both complexity science and geographical aspects[22] in order to complement such classic measures. The complex network perspective has

18 Ciceri et al. (1977)
19 Haggett and Chorley (1969)
20 Wang et al. (2009)
21 Nystuen and Dacey (1961); Vickerman et al. (1999); Bretagnolle et al. (2010)
22 Melançon and Rozenblat (2013); Gleyze (2013)

also been applied to all kinds of transport networks, such as maritime[23], airline[24], and railway networks[25]. The confirmation on their scale-free properties was not without recalling earlier literature on hub-and-spoke configurations[26]. In their study of three spatial networks where the airline configuration is formed by nodes (airports) and edges (scheduled flights), Gastner et al. (2004) underlined the influence of users' perception: the will to minimize the number of stops rather than the travel distance thus put in question the classic two-dimensional character of the network. When describing the topology of air and railway transportation networks in different countries based on nodes (cities of 50,000 or more inhabitants) and edges (direct routes operating more than a twice a day), Blumenfeld-Lieberthal (2009) did not consider the precise geometry of cities and transportation modes, nor did this work analyze the relationship between connectivity and economic activity (Gross Domestic Product).

Despite important progress on the network dimension, these analyses had excluded the empirical relationship between nodes and cities, socio-economic data and transportation topology, and the influence of a system of cities in the flow of resources. Based on the information above, next section presents significant efforts to operationalize such integration based on a system of cities connected by transportation modes.

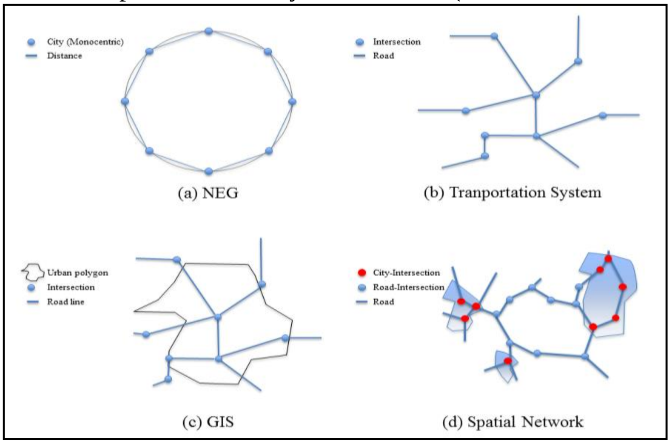
2. Systems of cities

The concept of a system of cities is one of the most widely used in urban studies. Nowadays, it is related to a network structure where each city (a collective spatial entity or contiguously built-up urban agglomeration) is interrelated to others and connected to multiple systems, for example social, economic, political, and transportation systems[27]. This concept has been used in economics and transport geography to understand the structure and dynamics of this type of spatial system. However, there are different interpretations on both perspectives about how to translate such a concept to system of cities, where the geometry of a city is more than a circular or monocentric shape in relation to the

23 Deng et al. (2009); Hu and Zhu (2009); Kaluza et al. (2010)
24 Li and Cai (2004); Guimera et al. (2005); Guida and Maria (2007)
25 Sen et al. (2003)
26 Fleming and Hayuth (1994); O'Kelly (1998)
27 Berry (1964); Churchman (1968); Pumain (2006); Pflieger et al. (2010)

Central Business District (CBD), and interactions among cities are more than the assumption of a symmetric costless migration. It is important to integrate graph theory, complex networks, GIS technology, and economic fields into a particular spatial network with geographic and socio-economic attributes in nodes and edges (Figure 2). In recent years, spatial network models have showed an increased flexibility to add not only geospatial, but also socio-economic information to nodes and edges[28]. Yet, there are very rare examples of a direct integration of urban attributes in network analysis. Therefore, contributions from transportation and economics are needed to fully understand the network configuration (i.e. static structure), while complex network models help to comprehend the dynamics in a system of cities connected by transportation modes.

<Figure 2> Interpretations of a system of cities (Source: own realization)



a) New Economic Geography: system of cities based on a circular structure with distance introduced symmetrically among cities. b) Transportation System: specific topology of transportation modes with a planar network related to road infrastructures. c) Geographic Information System: geospatial information based on urban polygons and road lines. d) Spatial Network: system of cities connected by transportation modes where nodes have different urban attributes such as population, density, income, and rental cost.

Transport geography, as an applied science, has generated specific models such as on corridor development[29] based on real-world examples,

[28] Barthélemy (2011); Batty (2011)

[29] Taaffe et al. (1963)

but with limited application to other fields. Depending on the spatial scale and time duration of the phenomena, the information needed for modeling increases or decreases its complexity[30]. More recent developments included graph theory and complex systems into geographic information science, for example the Geographical Information system (GIS) and the Global Positioning System (GPS), in order to offer a realistic view to large-scale spatial network models, as well as various metrics to study weighted graphs or "spatial weighted networks"[31]. For instance, Schintler et al. (2007) combined raster-based, graph theory, and complex systems to analyze Florida's road and railway networks, thereby getting closer to the integrated analysis of a system of cities.

The economic approach, on the other hand, has been attempted to describe the concentration and location of various urban activities from different perspectives such as urban economics, industrial organization, endogenous growth, and the NEG[32]. Although the transportation system is clearly seen as a key determinant of the flow of resources in the economy, it has not been introduced explicitly. Economics look at a system of cities formed by a collection of economic agents (consumers and firms) without or with limited spatial interactions, with static, comparative, and equilibrium methods as the basic core of the analysis. Two main principles have permeated the spatial approach in economics: a costless migration and a positive transport cost[33]. The most important principle indicates that distance does not affect the mobility of economic agents from one city to others. Henderson (1974), Wilson (1987), and Abdel-Rahman and Fujita (1990) included the conception of a system of cities in their models depending on the Dixit-Stiglitz assumptions of monopolistic competition and the null trading cost. However, they provided important economic mechanisms for understanding specialized and diversified cities.

The second principle including space in economic models is iceberg costs, which consists of an increasing fraction of product prices because of trade, mobility, and commuting between two locations[34]. Cities were treated as points in a circular or linear spatial structure as in the "racetrack

30 Bar-Yam (2004)
31 Barrat et al. (2005); Barthélemy (2011)
32 Abdel-Rahman and Anas (2004)
33 Krugman (1991); Abdel-Rahman and Anas (2004)
34 Krugman (1991); Fujita et al. (2001); Desmet and Rossi-Hansberg (2010)

economy"[35] where the distance between two locations is the length of shortest routes in the circumference. However, the distance is neutral because “regions are equally spaced”[36]. Related models that included distance to explain the effect of geography in socio-economic and transportation behaviors are spatial interaction and gravity models[37]. Their main problem is the translation of physics and biology mechanisms into social decisions. When forecasting and evaluating alternative plans for cities and regions, spatial flow models were based on a Newtonian to a Boltzmann entropy-maximization perspective[38].

The natural answer of economists to oppose this problem was the development of spatial econometrics that deals with spatial autocorrelation and heterogeneity (spatial interaction and structure). Anselin (1988, 2006) pointed out four important parts of these models: specification, estimation, test, and prediction. In particular, the model specification, as well as in econometrics, is the most important part of the analysis. Without economic foundations, such models obscure the potential for understanding spatial phenomena. Therefore, the main limitation of this perspective is the non inclusion of transportation modes in theoretical and empirical analysis, in particular the transportation topology.

3. Towards a better city/network integration

A number of works have integrated geographic and socio-economic elements in their analysis of spatial networks, but often in an indirect fashion. For instance, the analysis by De Montis et al. (2007) of inter-city commuter traffic based on GIS data did not consider geographic distances and other spatial characteristics. Nevertheless, their analysis displayed a positive correlation between network topology, traffic properties, and local demographic and economic data, suggesting a strengthening of central nodes. Another approach was to delineate polycentric urban areas based on inter-urban commuter flows and clustering methods but without direct inclusion of geographic and urban attributes of locations[39]. Lugo (2013) modeled a system of cities connected by road as a planar spatial network

[35] Krugman (1996)
[36] Fujita et al. (2001); Rossi-Hansberg (2005)
[37] Andersson et al. (2005, 2006); Gorman et al. (2007); Patuelli et al. (2007)
[38] Wilson (1967, 1970, 2012)
[39] Tissandier et al. (2013)

and proposed a preferential attachment process based on the size of cities and infrastructure data. Following the complex systems approach and using the increasingly available geospatial information, the author visualized a way to model a system of cities connected by transportation modes as a spatial network where the topology and geometry of such modes define and delimit the scale of the system, and the characteristics of each city are introduced by adding information in nodes and edges attributes. This type of specification could provide a generic network model that includes explicitly geographic, socio-economic, and infrastructure features of cities and modes.

Partly due to the absence of comparable data for urban studies, airline networks have become central in the analysis of systems of cities on various levels[40]. Some other works have analyzed the correlation between composite indicators of transport accessibility and urban size and function[41]. Wang et al. (2011) demonstrated the close relationship between the position of Chinese cities in airline networks (i.e. degree, closeness, and betweenness centralities) and their local socio-economic characteristics (i.e. total passenger traffic, urban population, and Gross Regional Product). Analyzing communication networks in the UK, Eagle et al. (2010) argues strong interdependencies between the diversity of connections and the economic well-being of localities. Another example on maritime flows is the work by Ducruet (2013) about the influence of commodity variety on network structure and flow distribution on the basis of orthodromic distance and urban areas. The study of interdependent spatial networks where diverse types of links connect cities is a buoyant research field[42], with many implications on the vulnerability of cities and transport systems (Figure 3). Ducruet et al. (2011) also highlighted the complementarities between air and maritime networks in the formation of a global urban hierarchy. This also can be seen in the work of Parshani et al. (2010) on the inter-similarity between coupled maritime and air transport networks, which shows that well-connected airports tend to couple with well-connected seaports in general, based on their respective geographic locations and on their topological attributes. Similar analyses

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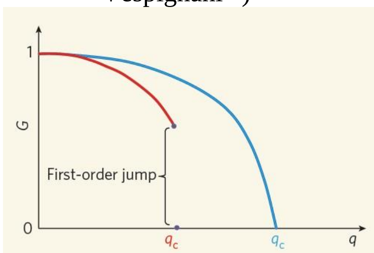
40 Amiel et al. (2005); Guimera et al. (2005); Choi et al. (2006); Tranos (2011)

41 Jin et al. (2010)

42 Zhang et al. (2005); Rosato et al. (2008); Buldyrev et al. (2010); Vespignani (2010)

have been done about French urban areas using seven different networks[43]. Yet, most of the aforementioned results remain highly static and call for more dynamic approaches.

<Figure 3> Impacts of node removal in coupled and simple networks (Source: Vespignani[44])



In the case of scale-free networks, the impact of node removal is stronger in a coupled network (red) than in a single network (blue), with G being the proportion of connected nodes and Qc the proportion of nodes needed to disconnect the whole network.

III. Network dynamics

Despite the development of transport and economic spatial models, the interrelations between them to analyze dynamics in a system of cities connected by transportation modes are missing. On the one hand, physicists and geographers have analyzed transport network dynamics based on topological attributes rather than urban attributes. On the other hand, economics has not solved the problem to incorporate network concepts and geospatial information in their assumptions and models. The topology is as important as the dynamics in the configuration and scale of a system of cities. A number of literature has investigated dynamics in complex networks, suggesting mechanisms for understanding topological changes based on nodes and edges properties[45]. However, most of the time such mechanisms apply to an abstract network space where geographical information is not included, as in numerous other methods proposed by sociology[46].

43 Berroir et al. (2012)
44 Vespignani (2010)
45 Newman et al. (2006)
46 Maisonobe (2013)

One possible solution is to analyze the evolution of spatial networks based on the preferential attachment mechanism as the basic model to connect transportation and economic perspectives. Its main problem is to determine or identify the initial conditions of the network, which are not trivial and affect the explanation of dynamics. Preferential attachment explains a discrete mechanism whereby a new node connects to others based on their level of connectivity or degree[47]. When including the geospatial location of nodes and edges, the probability to connect to others depend not only on the degree but also on the Euclidian distance[48]. That is, depending on the type of transportation mode, nodes prefer linking higher degree nodes or closer nodes[49]. Based on an airline network, Barrat et al. (2005) discussed the interplay between heterogeneous topology, weights and spatial constraints in a model of growing networks. They suggested that there is a strong correlation among connectivity, distance, and location of nodes that affect the structure of the network: "short connections go to small airports while long distance flights are directed preferentially towards large airports."

In accordance to infrastructure networks, the work of Yamins et al. (2003) presented a dynamic simulation model where roads grow based on two steps: the transportation potential ("total non-connected urban mass") between two cities, and the generation of a road based on its cost, where the denser the area and the longer the road, the more costly. This mechanism resembled a preferential attachment method because attributes of cities (location, demand for roads, and distance) affected the creation of a new road. In contrast with scale-free networks, land modes presented particular characteristics such as a limited number of connections in nodes[50]. Xie and Levinson (2009) also mentioned that the preferential attachment process explained the structure of airline networks but less the one of road networks due to the importance of cost and redundant routes.

To go beyond sole transportation network topology where node attributes guide connectivity, the inclusion of local socio-economic data for cities as additional GIS layers appear as a relevant solution. To analyze

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47 Albert et al. (1999)

48 Vinciguerra et al. (2010)

49 Barthélemy (2011)

50 Lämmer et al. (2006)

changes in the surface transportation networks, Xie and Levinson (2008) proposed a complex mechanism that removes an edge from the network depending on its performance. In contrast with the generative process used by Barrat et al. (2005), they applied a degenerative process that explains changes in the network topology (see Figure 4). This study provided a good method to combine GIS data, vector, and raster layers, to explain a cost-benefit behavior that causes the abandon of an edge. An implication of this is the possibility to include different types of information in nodes and edges that connect transportation and economic methods.

<Figure 4> Generative vs. degenerative methods (Source: Ducruet and Lugo[51])

(a) (b) (c)

a) Generative method displays an unconnected graph. b) A complex patter resulted by connecting or deleting links with small and large distance respectively. c) Degenerative method showing a complete planar graph.

Despite the increasing complexity caused by additional attributes on nodes, the dynamic process helps to understand further the relationship between socio-economic behavior and changes in the spatial network configuration. To date only few studies have used economic fundamentals in their analysis of preferential attachment in a system of cities connected by transportation modes. Lugo (2013) underlined the relationship between preferential attachment and a Cobb-Douglas function, which is commonly used in economics, in order to identify rules of connectivity in a system of cities linked by road networks. He suggested that such a function based on economic theory provided the base to explore different types of preferential attachment mechanisms in which geographic, socio-economic, and infrastructure information is included. Furthermore, Lugo and

51 Ducruet and Lugo (2013)

Gershenson (2013) analyzed a system of cities connected by one transportation mode to discover ancient routes in the Aztec Empire based on current road configuration.

IV. Conclusion

All in all, we reviewed important literature related to cities and transport networks to discuss how their further integration may contribute to improve the current state of shipping and logistics research, not only to upgrade the system modeling of spatial networks, but also to advance the respective theoretical models. This suggests an interdisciplinary approach to enhance our understanding of such systems.

The science of complexity provides the relevant framework to merge models of systems of cities and transportation modes. In particular, the increasingly available geospatial data of cities and modes could be used to specify and analyze the structure of spatial networks, and the application of the economic theory could support hybrid mechanisms to analyze network dynamics. Therefore, transport networks and urban studies, nowadays, can include mutually and explicitly their characteristics in research.

One of the most important limitations of this agenda lies in the fact that interdisciplinary analysis is not trivial. It requires that the scientist combines different knowledge and technical skills to produce novel ideas. In this case, economics, geography, and transportation insights, and GIS technology, complex network measures, and spatial econometrics models and techniques are tied by complexity. It is therefore likely that the application of such perspective increases only moderately in the coming years. It also depends on the research focus, as such integrated approaches could contribute to better understand both transport / carrier strategies and urban development / planning strategies.

Taken together, these ideas support strong recommendations for scholars, policymakers, and industrial practitioners to include as soon as possible an interdisciplinary method and analysis in their research to achieve a better understanding of shipping and logistics systems and planning highly practical spatial networks on different spatial scales.

Future research should be done to investigate how practical and time-consuming is this method in designing and operating such systems.

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